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14. ABSTRACT
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15. SUBJECT TERMS
diffractive optics; scanner correction; resonant scanner

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Binary Chirped Grating Diffractive Element for Sinusoidal to Linear Scanning Conversion: The Beam Propagation Design

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Abstract

We fabricated and tested our previously deigned optical correction element with zoom capability to convert nonlinear sinusoidal scans into linear scans. The design methodology is based on derivating a graded index of refraction device as a reference design and converting the graded index of refraction into an amplitude or phase binarized diffractive element. Our graded index of refraction derivation is based on the propagation of an electromagnetic wave in an inhomogeneous media. Our experimental results showed the first order diffraction linearization of the sinusoidal scanning which is in agreement with our theory. The second order linearization was also discovered experimentally which was not predicted by the theory. The tests of the diffractive element device indicate that the linearization has small errors.

Subject terms: diffractive optics; scanner correction; resonant scanner.

Diffractive optics technology can be used to provide a planar, low cost solution to replace conventional 3-D refractive optics[1]. The diffractive elements have been utilized applications such as thermal aberration correction in high power solid state lasers[2], optical pattern generation[3], and optical free space interconnects[4]. High speed resonant laser scanners, utilizing oscillating mirrors operating at their natural resonant frequency, provide a nonlinear sinusoidal scan; consequently, at the limits of the scan, the scan field is significantly compressed.

Here we describe the fabrication and the test results of our previously designed single optical element that provides such a correction. While the use of diffractive optics for aberration correction is well established, to our knowledge, we know of no previous use in this area of scanning corrective optics[5]. We use a beam propagation in inhomogeneous media approach[6] to create the reference refractive element, and then convert the refractive element into a binarized diffractive element.

In our design, we used the beam propagation of an electromagnetic wave in an inhomogeneous medium to derive the graded index of refraction n(y) of our corrective element, followed by binarization and fabrication of the appropriate diffractive element. In Figure1, the refractive gradient causes the incident beam at angle θ_2 to deflect and propagate at angle θ_3. The input sinusoidal beam angle, θ_2, is given by $\theta_2 = \theta_{20}\sin\omega t$ where θ_{20} is the maximum amplitude of the sinusoidal angle, and θ_3 is the output deflection angle. To facilitate analysis, we invoke a co-located virtual linear scanner whose scanning angle θ_1 is proportional to time, i.e. $\theta_1 = gt$.

In the paraxial approximation, in Figure 1, the output deflection angle from the corrective element is:

$$\theta_3 = \frac{Z_1\theta_1 - Z_2\theta_2}{Z_1 - Z_2}. \quad (1)$$

Z_1 is the distance between the target and the scanner, and Z_2 is the distance between the corrective element and the scanner.

We derived the graded index of refraction of the corrective element from the eikonal equation for beam propagation in an inhomogeneous media[6],

$$\ln(n) = \frac{1}{l}\left(\frac{Z_1}{Z_1 - Z_2}\right)\left[\frac{g}{\omega}\left(y\sin^{-1}\left(\frac{y}{Z_2\theta_{20}}\right) + \sqrt{Z_2^2\theta_{20}^2 - y^2}\right) - \frac{y^2}{2Z_2}\right]. \quad (2)$$

For scanning at remote distances ($Z_1 >> Z_2$, so $Z_1/Z_1 - Z_2) \approx 1$), and by expressing the scan parameters in terms of y_0 ($y_0 = Z_2\theta_{20}$), Equation 2 can be approximated as:

$$\ln(n) = \frac{1}{l}\left[\frac{g}{\omega}\left(y\sin^{-1}\left(\frac{y}{y_0}\right) + \sqrt{y_0^2 - y^2}\right) - \frac{y^2}{2Z_2}\right], \quad (3)$$

describing the graded index of refraction of the element as a function of y. The ratio g/ω determines the zooming capability of the corrective element to be either equal, less, or larger than the original uncorrected field of view. Also, in order for the element to maintain the linear portion of the sinusoidal scanning near the nodal line, g = ω. The detailed derivation has been published elsewhere[5].

To binarize the graded index of refraction into the corresponding diffractive element, we utilize the following amplitude binarization algorithm for the transmitivity:

$$T = \begin{cases} 2(m-1)\pi < \frac{2\pi}{\lambda}nl < 2m\pi & = 0 \\ (2m-1)\pi < \frac{2\pi}{\lambda}nl < (2m+1)\pi & = 1 \end{cases} \quad (4)$$

Figure 2 shows plots of the graded index of refraction of the corrective element for three values of the ratio g/ω: 0.5, 1, 2, for y_o= 1 cm, and for three values of y_o: 2cm, 1cm and

0.5 cm, for $g/\omega=1$. We assumed that the thickness of the element was $l = 1$ mm. Figure 2(A) covers the case where the corrective element dimension (y_0) is the constant parameter while the ratio of g/ω varies, which Figure 2(B) covers the opposite situation. The plots reveal that increasing either g/ω or y_0 of the corrective element increases the offset value of the index of refraction.

Figure 3 shows a photograph of the actual device fabricated, representing the binary amplitude version of the diffractive elements for one of the cases presented in Figure 2, with $g/\omega = 1$ and $y_o=1$ cm.

We observe that the binary diffractive element consists of a chirped grating whose frequency increases as the deflection angle increases.

The amplitude version of the diffractive element design was fabricated for an aperture size of 1 cm ($y_o = 1$ cm), on a single standard chrome-on-glass 4"x 4" photomask by a commercial vendor using AutoCAD™ files generated InHouse from the design calculations. The photomask was mounted with the grating lines of the element vertical orientation, and the incident angle of a He-Ne laser beam was varied by rotating a mirror in the optical path. The optical center of this steering mirror was 10 cm away from the center of the element under measurement. Incident and diffraction angles were calculated from linear measurements of the beam position of the laser spot on a distant screen (~ 5m from the element). The entire arrangement is shown in Figure 4. The diffraction patterns of the laser beam diffracted off of two different locations on the diffractive element are shown in Figure 5. Figure 5(A) shows the two laser beam locations on the diffractive element, 5(B) and 5(C) are the diffraction patterns photographs taken of the screen. The separation between the orders increases as the beam moves towards the edges, as we

expected. The output angle θ_3 was plotted against the arcsine of the ratio of the incident angle θ_2 of the diffracted beam and the maximum scan amplitude θ_{20} ($\theta_{20} = y_0/Z_2$) for both the first and second orders of diffraction. The second order linearization was discovered experimentally which was not predicted by the theory. Excellent agreement with the design equations was obtained for the first order. The plots of both the first and the second orders linearization are shown in Figures 6(A) and 6(B) respectively.

In conclusion, we have designed, fabricated and tested a diffractive corrective element with a zoom capability for converting nonlinear sinusoidal scanning into linear scans. We derived the graded index of refraction of the corresponding refractive device based on the propagation of an electromagnetic wave in an inhomogeneous media followed by amplitude binarization according to our binarization algorithm in Equation 4. Optical characterization of the fabricated devices showed excellent agreement between the measured diffraction angles and the design. The second order linearization was observed experimentally which was not predicted by the theoretical modeling. The performance of the diffractive device should provide performance adequate for many applications.

Acknowledgments

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3. P. Blair, H. Lpken, M. R. Taghizadeh, and F. Wyrowski, "Multilevel phase-only array generators with a trapezoidal phase topology ," Appl. Opt. 36, 4713-4721 (1997)
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Figure Captions:

Fig. 1. Ray Diagram of Resonant Scanner with Refractive/Diffractive Corrective Element.

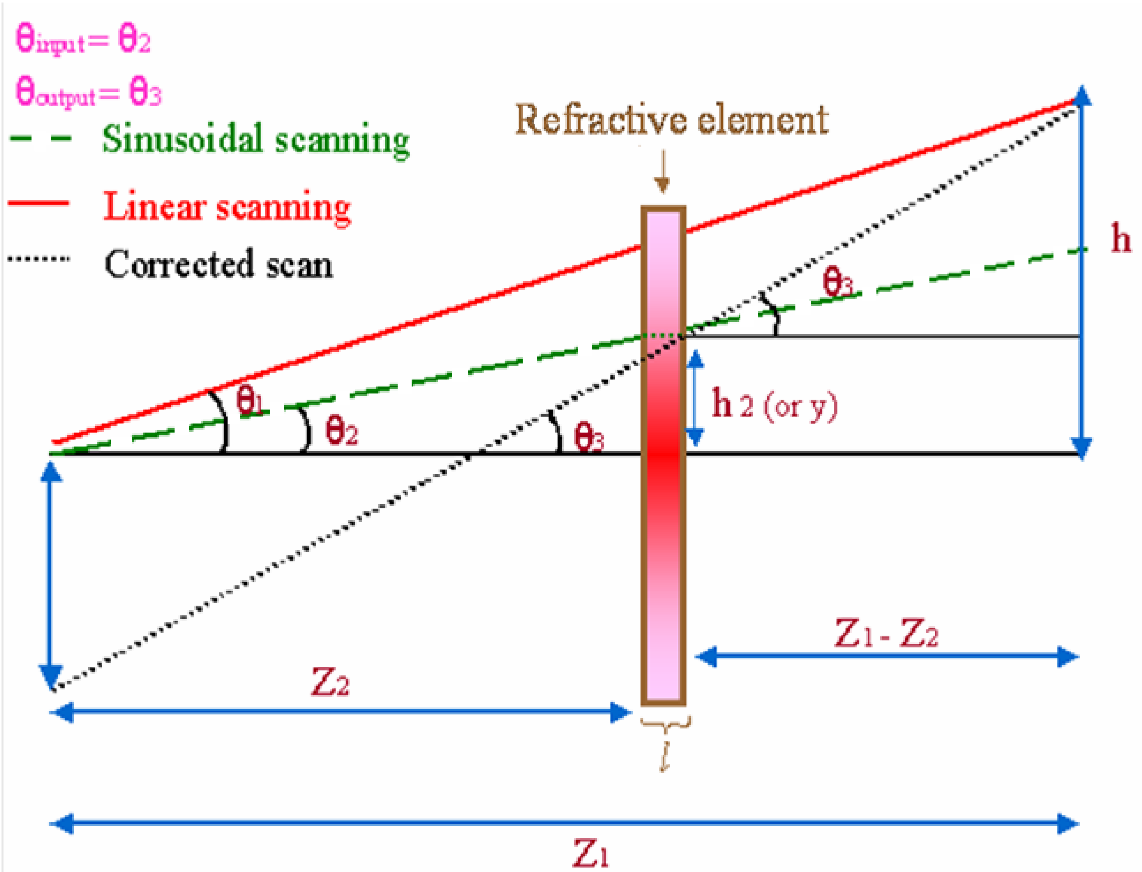
Fig. 2. Calculated index variations as a function of distance from the optical axis, y, at A) constant dimension y_0 = 1 cm, variable g/ω and B) variable dimension, constant g/ω =1.

Fig. 3. Photograph of fabricated binarized diffractive element for g/ω= 1, and dimension y_0 = 1 cm.

Fig. 4. Laser diffraction setup for the measurement of the performance of the diffractive element.

Fig. 5. Photograph of the diffraction patterns, (A) two spots of the diffractive element was illuminated by the laser beam to generate the diffraction patterns shown in (B) and (C).

Fig. 6. Plots of experimental data of the input angle vs. the arcsine of the ratio of the output diffraction angle and the scan amplitude constant θ_{20}, for A) 1st, and B) 2nd orders of diffraction.



$\theta_{input} = \theta_2$
$\theta_{output} = \theta_3$
Sinusoidal scanning
Linear scanning
Corrected scan
Refractive element
h
θ_3
θ_1
θ_2
θ_3
h 2 (or y)
$Z_1 - Z_2$
Z_2
l
Z_1

Figure 1

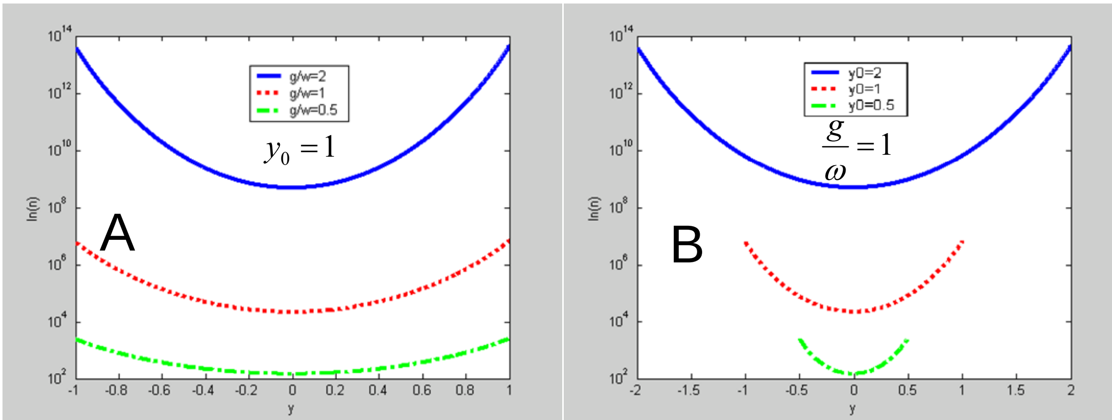


Figure 2

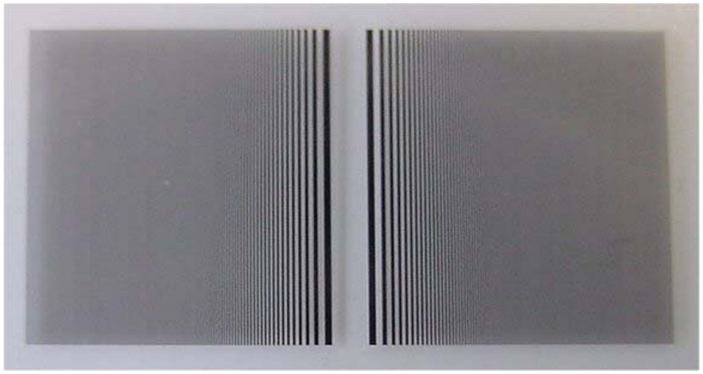


Figure 3

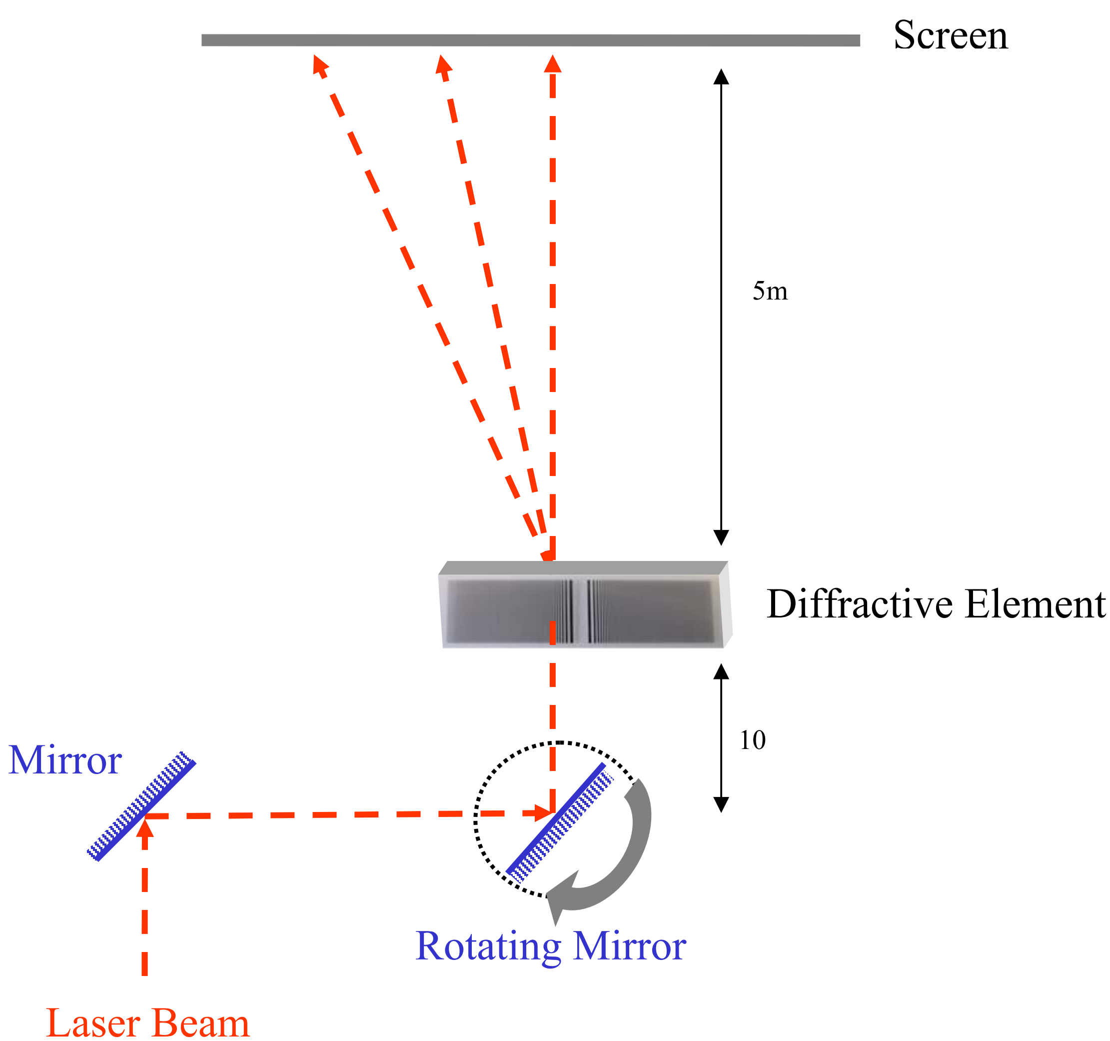

Screen
5m
Diffractive Element
10
Mirror
Rotating Mirror
Laser Beam

Figure 4

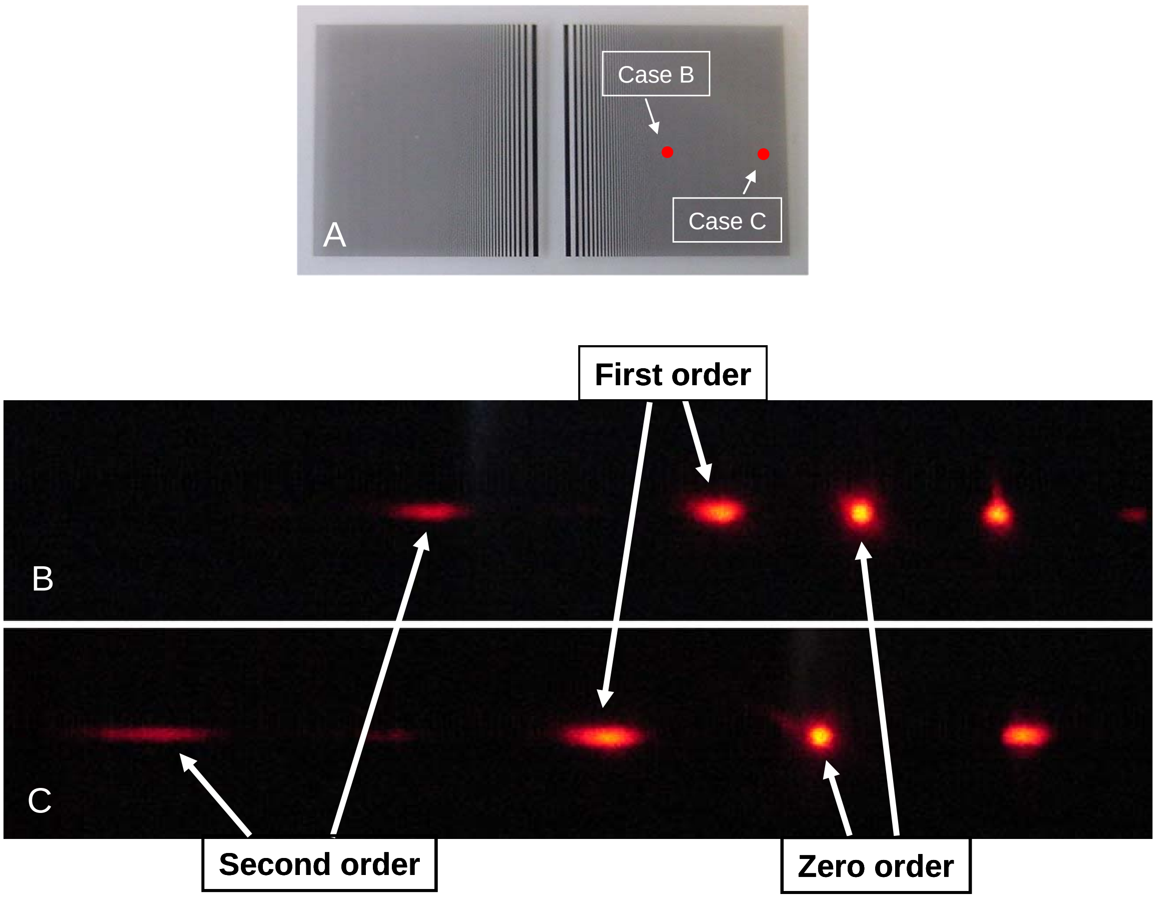


Figure 5

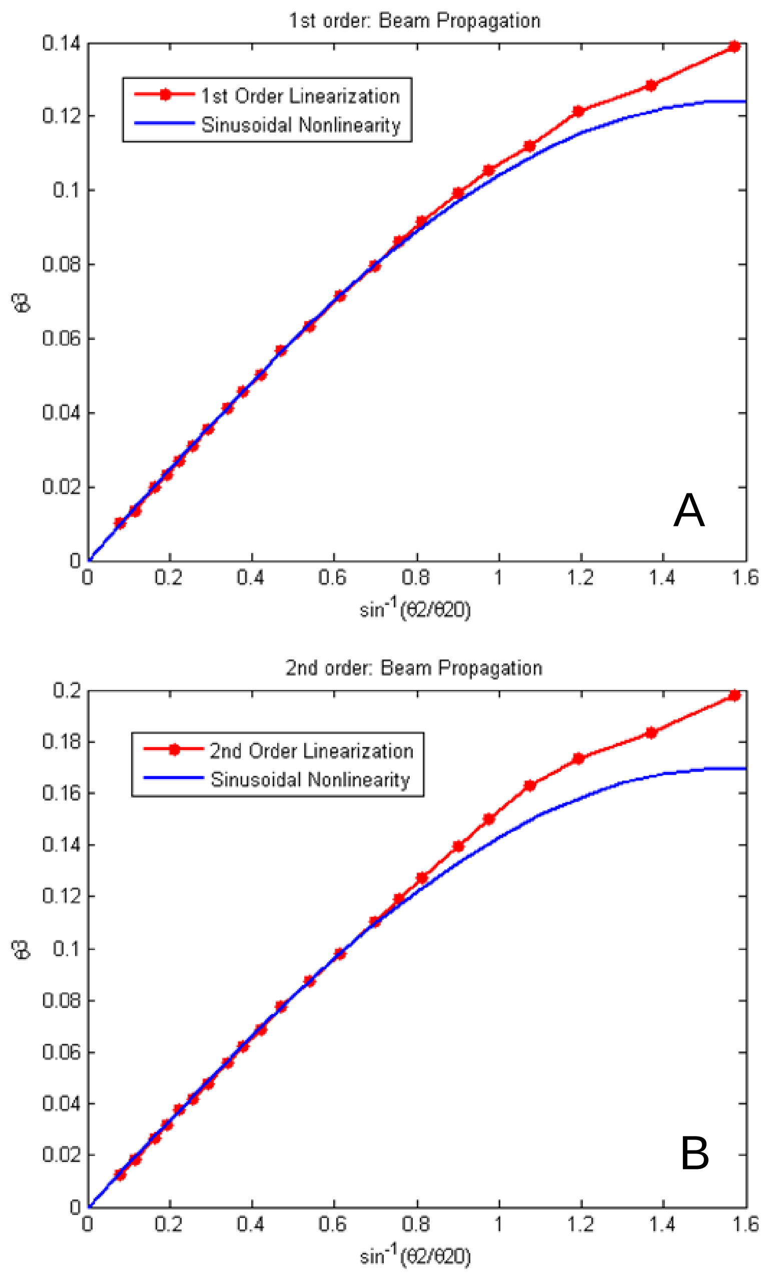

1st order: Beam Propagation
1st Order Linearization
Sinusoidal Nonlinearity
θ3
sin⁻¹(θ2/θ20)
A
2nd order: Beam Propagation
2nd Order Linearization
Sinusoidal Nonlinearity
θ3
sin⁻¹(θ2/θ20)
B

Figure 6

Response to the reviewers comments for manuscript number: 79852, entitled "Binary Chirped Grating Diffractive Element for Sinusoidal to Linear Scanning Conversion: The Beam Propagation Design"

Reviewer 1
This paper deals with the design, fabrication and testing of a diffractive corrector. This corrector is made to convert non linear sinusoidal scanning into linear scanning. Most of the paper is focused on the design. End of the paper describes manufacturing and testing of the part.

Technical content:

Page 1 to 4 (bottom) of the manuscript were already published in the following references [1] "Diffractive element design for resonant scanner angular correction", Khoury et al, AO 45-27, 2006 [2] "Diffractive element design for resonant scanner angular correction: a beam retardation approach", Khoury et al, AO 45-32, 2006 Manufacturing and testing are briefly described in page 5. A discussion on residual non linearity after correction and potential impact of manufacturing errors would have been suitable.

This paper is the experimental results of our previous work which is not ever reported before.
An explanation for the residual nonlinearity after correction has added to the paper.

Presentation:
Manuscript is easy to read.
Some modification shall be made to figure for a better understanding
Fig 1: colour differences between sinusoidal and linear scans are difficult to see when printed in black and white. Please modify.
Reference 7, called on page 4, is missing in the bibliography.

Figure 1 has been fixed and references have been rearranged and modified.

Appropriateness
Subject of this paper is appropriate for a publication in Optics Letter. But since most of the presented material has already been published before, the paper in its current form offers only incremental improvement to existing work. Therefore, we suggest rejecting this paper.

This paper is not an incremental improvement to our previous work. This paper is the experimental verification of our previously reported algorithm. We believe in appropriateness of this paper for optics letter publication since this paper is the completion of our work and has new experimental results.